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Luminosity measurement at ILC

I. Božović Jelisavčić[a], S. Lukić[a], M. Pandurović[a] and I. Smiljanić[a]

[a]*Vinča Institute of Nuclear Sciences, University of Belgrade, Serbia*
Address, Country
E-mail: `ibozovic@vinca.rs`

ABSTRACT: In this paper we propose the method of luminosity measurement at the future linear collider ILC that estimates and corrects for the impact of the dominant sources of systematic uncertainty originating from the beam-induced effects and the background from physics processes. Some systematic corrections can be done in a simulation independent manner. With the specific event selection, different from the isolation cuts based on topology of the signal used at LEP and with the corrective methods we introduce, overall systematic uncertainty of the luminosity measured in the peak region above 80% of the nominal center-of-mass energy meets the physics requirements to be at the permille level at all ILC energies.

KEYWORDS: Accelerator modeling and simulations (multi-particle dynamics; single-particle dynamics), Detector modeling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc.), Calorimeter methods.

Contents

1. Introduction

Integrated luminosity measurement at a future linear collider will be performed by counting Bhabha events reconstructed in the luminometer fiducial volume within specified event selection. To match the physics benchmarks (i.e. W-pair production fermion pair-production, cross-section measurements) that might be of particular interest for the new physics, luminosity should be known at the level of 10^{-3} or better [1]. In this paper we present the method of measurement optimized to meet the requirements for luminosity precision. Systematic effects are estimated and either taken as full-size effects or corrected in a simulation independent manner. In summary, we prove that the luminosity can be measured in the peak region above 80% of the nominal center-of-mass energy with a relative precision of a few permille at all ILC energies. In addition, luminosity spectrum can be precisely reconstructed in the same energy region from the experimentally measurable quantities.

Finely granulated calorimeters of high energy and polar angle resolution are foreseen to instrument the very forward region at ILC. Luminometer at a future linear collider will be designed as a compact sampling calorimeter with a Moliere radius of approximately 1.5 cm [2]. To reduce systematic biases from the mechanical precision of the alignment, a laser based monitoring system has been developed for ILC to control the position of the luminometer over short distances within a micron [3]. ILD detector model [1] for ILC is assumed at a center-of-mass energies of 500 GeV and 1 TeV. Design of the luminometer is described in Chapter 2.

With the rising energy and the bunch density, one of the main uncertainties in luminosity measurement at a future e^+e^- collider at TeV energies comes from the effects induced by space charges of the opposite beams. Beamstrahlung and electromagnetic deflection induced by the field of the opposite bunch, together with the initial state radiation (ISR), result in the change of the four-vectors of the initial and final state particles consequently causing the deviation of the polar angles and counting losses of the signal in the luminometer. Dominating beamstrahlung effects are particularly pronounced at higher center-of-mass energies, resulting in 12.8% at 500 GeV at ILC [4] up to 70% counting losses in the 3 TeV CLIC case [5]. Corrective methods developed to take this into account are reviewed in this paper in Chapters 4.1.1 and 4.1.2.

Due to the precision requirements of luminosity measurement, background from physics processes is discussed as another important source of systematic uncertainty. Electron spectators from the four-fermion processes can be misidentified as a signal since they are emitted at low angles and with a high energy. These processes can be, in principle, efficiently suppressed by the LEP type isolation cuts based on the signal topology [6, 7] that can not be directly translated to the linear collider case where beam-induced effects have to be simultaneously taken into account. Physics background in luminosity measurement is discussed in detail in Chapter 4.2.

2. Luminometer at ILC

International Large Detector (ILD) [1] is one of the two systems of particle detectors developed for ILC. ILD combines excellent tracking and finely-grained calorimetry systems, which enables ILD to reconstruct the energy of individual particles, using particle flow algorithm [8]. The precision of 3 to 4 percent can be achieved in the jet energy reconstruction [1]. To provide jet separation in multi-jet processes, electron identification down to the lowest polar angles, as well as a good hermeticity of the ILD detector, the very forward region is instrumented with the two special calorimeters: luminometer designed to measure the rate of the low angle Bhabha scattering and the beam calorimeter that will allow fast luminosity estimate and measurement of the beam parameters. Layout of the very forward region of the ILD detector is illustrated in Figure 1 (left) [1].

Luminometer at ILC is foreseen as a sampling silicon/tungsten calorimeter, consisting of 30 one radiation length (3.5 mm) thick absorber planes, followed by segmented silicon sensor planes. To keep the Moliere radius of 1.5 cm, 1 mm sensor gaps are provided. As illustrated in Figure 1 (right), tungsten disks are precisely positioned using 4 bolts. The system is additionally stabilized by steel rings. Reconstruction of the polar angle of an electron is influenced by the sensor segmentation that is optimized to 48 azimuthal and 64 radial divisions to provide the polar angle resolution $\sigma_\theta = (2.20 \pm 0.01)\cdot 10^{-2}$ mrad and the polar angle bias $\Delta\theta = (3.2 \pm 0.1)\cdot 10^{-3}$ mrad [2]. Each of these uncertainties contribute to the relative uncertainty of luminosity measurement of $\Delta L/L = 1.6\cdot 10^{-4}$ [2]. Luminometer is positioned at 2.5 m from the IP, with the geometrical aperture between 31 mrad and 78 mrad. Inner and outer radius are 80 mm and 195.2 mm respectively. Since the cross-section for Bhabha scattering is falling with the polar angle as $1/\theta^3$, the inner aperture of the luminometer has to be known with a few tens of microns or better [9] to keep the counting uncertainty below permille.

With 30 radiation lengths of tungsten as the absorber, high energy electrons and photons deposit almost all of their energy in the detector. The relative energy resolution σ_E/E is parametrized

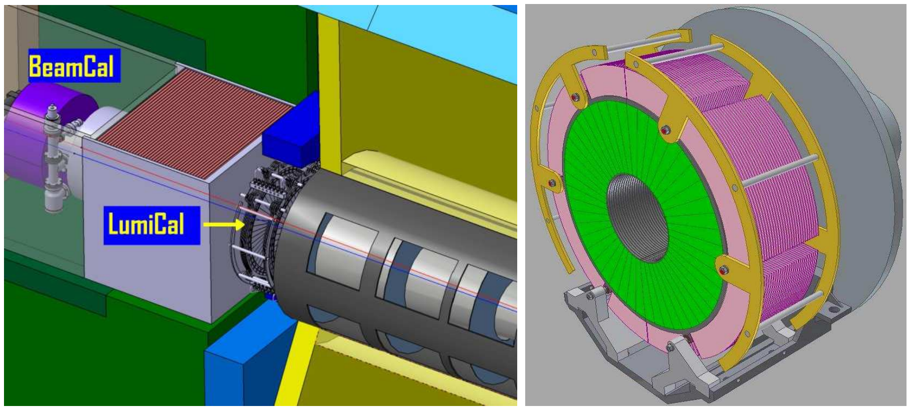

Figure 1. Layout of the very forward region of ILD (left). Mechanical structure of the luminosity calorimeter for ILD (right).

as:

$$\frac{\sigma_E}{E} = \frac{a_{res}}{\sqrt{E_{beam}(GeV)}}, \tag{2.1}$$

where E and σ_E are, respectively, the central value and the standard deviation of the distribution of the energy deposited in the sensors for a beam of electrons with energy E_{beam}. The sampling parameter a_{res} is usually quoted as the energy resolution and it is estimated to be $a_{res} = (0.21 \pm 0.02)\ \sqrt{GeV}$ [2] for electron showers located inside the fiducial volume of the luminometer. Detector fiducial volume, where σ_E/E is practically constant over θ, extends from 41 to 67 mrad.

3. Event simulation

3.1 Simulation of the signal influenced by the beam-induced effects

To simulate the influence of the beam-induced effects on signal, the Guinea-PIG software 1.4.4 [11] was employed to simulate the collisions of bunches. At the point when the initial four-momenta of the colliding e^-e^+ pairs are generated, the decision is made by Guinea-PIG whether the Bhabha scattering will be realized in the collision. The decision is made randomly, based on the cross-section for the Bhabha scattering of the electron-positron pair of a given energy. If Bhabha event is to be realized, the final four-momenta are picked from a file generated at the nominal ILC center-of-mass energy (500 GeV, 1 TeV) with the BHLUMI V4.04 generator [12]. Bhabha events are generated with the scattering angle in the center-of-mass frame around the luminometer fiducial volume. The momenta are then scaled to the center-of-mass energy of the colliding pair, rotated to match the collision axis and then boosted back to the laboratory frame. Finally, electromagnetic deflection of the final state is simulated using the Guinea-PIG feature to predict the final deflection angles.

The standard beam-parameter set from the ILC Technical Progress Report 2011 [13] was used as the basis for both 500 GeV and 1 TeV simulations. Variations of individual beam-parameters are taken into account in order to determine the influence of the beam-parameter uncertainties on

the performance of the presented method (Chapter 4.1.1). Simulated beam-parameter variations include:

- Symmetric bunch size variations by ± 10 and $\pm 20\%$ and one-sided variations by +20% in σ_x, σ_y, σ_z;
- Symmetric bunch charge variations by ± 10 and $\pm 20\%$ and one-sided +20% variation;
- Beam offset in x- and y-direction by up to one respective bunch RMS width.

Thus, 25 sets of beam parameters were simulated in total for each of the two ILC energy options. In each simulation, one single beam parameter was varied with respect to its nominal value. Between 1.5 and 4 million Bhabha events were generated in each simulation. The interaction with the detector was approximated in the following way:

- The four-momenta of all electrons and photons, that are treated as indistinguishable, are summed together in the 5 mrad cone around the most energetic shower. The 5 mrad criterion corresponds closely to the Moliere radius of the high-energy showers in the LumiCal [14]. The initial beamstrahlung photons were not included as they are emitted close to the beam axis. For synchrotron radiation, the characteristic emission angles are of the order $1/\gamma$, being smaller than 10^{-3} mrad for the electron energies in the TeV range, therefore the four-momenta of photons emitted by the outgoing electrons can be added.
- The energy resolution of the luminometer is simulated by adding random fluctuations to the final particle energies. The random fluctuations were sampled from the Gaussian distribution with the energy-dependent standard deviation.
- The finite angular resolution of the luminometer is included by adding random fluctuations to the final particle polar angles corresponding to the luminometer resolution in polar angle as given in Chapter 2.

3.2 Simulation of physics background

Four-fermion events $e^+e^- \to e^+e^- f\overline{f}$ are generated at the tree level at 500 GeV and 1 TeV center-of-mass energy, with the total corresponding cross-section of $\sigma_{bck} = (5.1 \pm 0.1)$ nb and $\sigma_{bck} = (0.8 \pm 0.1)$ nb respectively, using WHIZARD-V1.2 event generator [16]. Parameters of the event generation are tuned using $e^+e^- \to e^+e^- c\overline{c}$ to describe the experimental results obtained by several experiments at lower energy at PETRA and LEP accelerators [15]. Thus the physics background is generated under the following assumptions:

- Mandelstam invariant mass of the outgoing lepton pair is greater than 1 GeV^2,
- Momentum transfered by the photon exchange is greater then $1 \cdot 10^{-4}$ GeV,
- Events were generated within the polar angle range between 0.05 and 179.95 degrees to avoid the divergence of the cross-section at low polar angles.

Matrix elements for the leading order Feynman diagrams are computed using O'Mega generator [17]. The total sizes of samples correspond approximately to 1 million of background events generated at each ILC energy. The cross section for background processes integrated in the polar angle range of the luminometer fiducial volume is about a percent of the generated one.

Influence of physics background is estimated against the signal samples of 20 pb^{-1} of Bhabha events, with the cross-sections in the luminometer fiducial volume of σ_s=(4.689$\pm$ 0.001) nb and σ_s=(1.197$\pm$0.005) nb at 500 GeV and 1 TeV center-of-mass energy, respectively. Estimated errors of the cross-sections are statistical. Signal is simulated with the BHLUMI event generator[12] implemented in BARBIE V5.0 [18], a GEANT4 [19] based detector simulation of the luminometer at ILC.

4. Luminosity measurement

4.1 Method of luminosity measurement

Luminosity at electron-positron collider is measured using Bhabha scattering at low angles ($e^+e^- \to e^+e^-(\gamma)$ as a gauge process, which is calculable with the great precision in QED. This is dominantly electromagnetic process (99% at ILC energies [20]) of one-photon exchange in the t-channel for which the cross-section calculations with relative uncertainty better than 10^{-3} are available [21]. Luminosity at ILC will be measured by counting Bhabha scattering events that are recognized by coincident detection of showers in the two halves of luminometer. Unless distorted by the beam-induced effects, these showers are collinear and carry the most of the available center-of-mass energy. The luminosity integrated over certain period of time is calcuable as the number of Bhabha events, N, divided by the theoretical cross-section for the Bhabha scattering, σ.

$$L = \frac{N}{\sigma} \tag{4.1}$$

In the most general view, equation (4.1) translates to:

$$L = \frac{N(\Xi(\Omega_{1,2}^{lab}, E_{1,2}^{lab}))}{\sigma(Z(\Omega_{1,2}^{CM}, E_{1,2}^{CM}))} \tag{4.2}$$

where $\Omega^{lab(CM)}, E^{lab(CM)}$ stands for angular parameters and energy of the final state particles in the laboratory (center-of-mass) frame, while $\Xi(Z)$ represents the applied selection function itself. Equation (4.2) emphasizes that Ξ and Z operate on kinematical arguments in different reference frames. The cross section is typically calculated by the Monte Carlo integration using an event generator in the center-of-mass frame of the process, under assumptions expressed by Z. On the other hand, Bhabha particles are experimentally reconstructed in the laboratory frame under certain selection Ξ. In addition, the final state four-momenta are affected by the beam-beam effects. Because of random and asymmetric emission of the beamstrahlung and ISR, the center-of-mass frame of the Bhabha process is different for every colliding pair and in general it does not coincide with the laboratory frame. The resulting axial boost of the outgoing particle angles induces angular acceptance loss of the signal in the detector fiducial volume. An additional systematic bias of the order of 1 – 2 permille [10] is induced by the electromagnetic deflection (EMD) of the outgoing Bhabha particles in the field of the opposite bunches.

At LEP, angular counting losses were usually addressed by applying selection in polar angles of the final state particles that is asymmetric with respect to the forward and backward side of the luminometer [22, 23, 24]. In order to minimize the beam induced effects on Bhabha counting rate, the similar techniques was proposed for ILC as well [9, 10] where the beam-beam effects are much more intense. The above mentioned corrective techniques are simulation dependent and the systematic uncertainty of luminosity measurement depends on the knowledge of the beam parameters (i.e bunch sizes) [10]. To overcome these limitations, we introduce a concept in which one seeks to define Ξ and Z in such a way that the counting rate is independent of reference frames in which these functions act. This is satisfied to a very good approximation by the *collision-frame method* we have recently proposed for CLIC [5]. This method, described in the following chapter, corrects on the event-by-event basis for the counting loss of Bhabha events induced by beamstrahlung and ISR, using the relativistic velocity of the electron-positron system β_{coll} after the emission of ISR and before the emission of FSR. As it will be shown, corrections to Bhabha counts can be determined in a simulation independent manner and from the experimentally measurable quantity β_{coll}. The EMD effect requires different approach that will be discussed in Chapter 4.1.2. In addition, event selection has to be established in a way to suppress the background from physics processes present in the very forward region (Chapter 4.2).

4.1.1 Collision-frame method

As said in Chapter 1, counting losses at ILC due to beamstrahlung are of the order of 10%. To reach the luminosity uncertainty at a permille level this effect should be corrected for with the same precision.

Collision frame is defined as the center-of-mass frame of the electron-positron system after emission of ISR and before the emission of FSR. In this reference frame Bhabha scattering is described by the unique scattering angle θ^{coll}, due to the momentum conservation principle. Since the kinematics of the detected showers corresponds to the system after ISR, the relativistic velocity of the collision frame w.r.t. the laboratory frame β_{coll} can be calculated to a good approximation from the measured polar angles. If β_{coll} is approximated to be collinear with the z-axis, what comes from the fact that the beamstrahlung photons are emitted very close to the beam pipe, β_{coll} can be expressed as:

$$\beta_{coll} = \frac{sin(\theta_1^{lab} + \theta_2^{lab})}{sin(\theta_1^{lab}) + sin(\theta_2^{lab})} \tag{4.3}$$

Movement of the collision frame w.r.t the laboratory frame translates into counting loss of Bhabha events from the detector fiducial volume, effectively decreasing acceptance of the luminometer.

As illustrated in Figure 2, events with the larger β_{coll} are more probable to miss the luminometer fiducial volume. For β_{coll} larger than some critical value β^* (approximately 0.24 [25]), events are irreducibly lost. However, for $\beta_{coll} \leq \beta^*$ counting loss can be corrected by appropriate weighting $w(\beta_{coll})$ on the event-by-event basis.

$$w(\beta_{coll}) = \frac{\int_{\theta_{min}}^{\theta_{max}} (\frac{d\sigma}{d\theta})\, d\theta}{\int_{\theta_{min}^{coll}}^{\theta_{max}^{coll}} (\frac{d\sigma}{d\theta})\, d\theta} \tag{4.4}$$

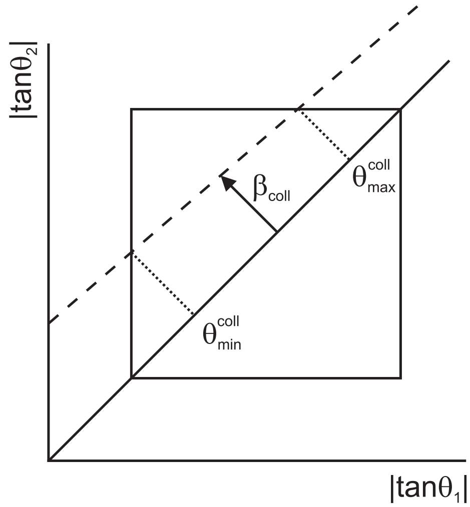

Figure 2. Illustration how the events with the larger collision-frame velocity β_{coll} escape the detector fiducial volume (square). $\theta^{coll}_{min,max}$ stand for the minimal (maximal) value of the scattering angle in the collision frame that is available for events with β_{coll} to be identified within the luminometer acceptance.

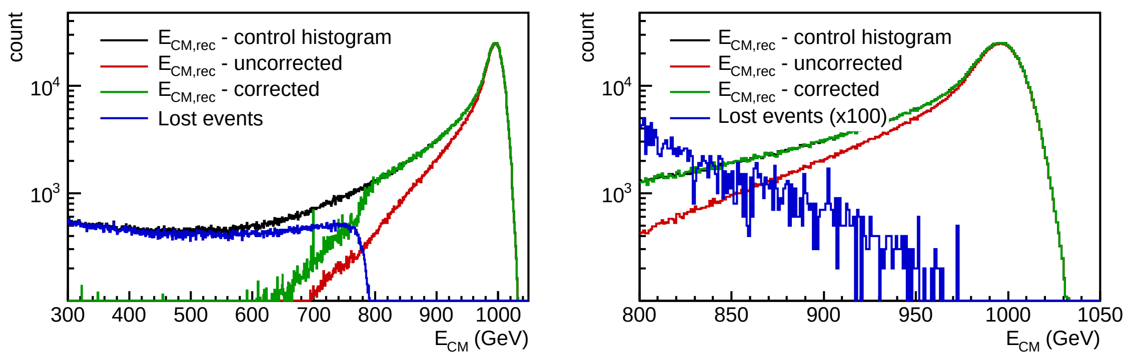

Figure 3. Correction of the signal counting loss due to beamstrahlung and ISR at 1 TeV ILC (left). On the right, the same distributions are zoomed above the 80% of the nominal center-of-mass energy.

To evaluate the performance of the collision-frame method, center-of-mass energy $E_{CM,rec}$ is reconstructed for events unaffected by the beamstrahlung and ISR that serves as a control sample, events affected by beamstrahlung and ISR (uncorrected), events corrected by the weighting method as described above and finally, for events whose collision-frame velocity is sufficiently large that they are irrecoverably lost from the detector fiducial volume. This is all illustrated in Figure 3 for 1 TeV ILC case.

As can be seen from Figure 3, despite severe counting losses due to beamstrahlung and ISR, the agreement after correction is excellent above 80% of the nominal center-of-mass energy (800 GeV). The range below 80% of the nominal center-of-mass energy is dominated by events for which β_{coll} is so high that the one of outgoing particles is always lost. Since high vaue of β_{coll} is kinematically connected with high energy loss, the number of such events is very small above 80% of the nominal center-of-mass energy. The presence of a small number of high-β_{coll} events at energies above 80% of the nominal center-of-mass energy is visible in the zoomed figure (Fig.

3, right), where these events are scaled by a factor 100. In these events $\vec{\beta}_{coll}$ has a relatively high radial component due to the off-axis radiation before collision. For these events assumption that $\vec{\beta}_{coll}$ is collinear with the beam axis is not valid anymore. The relative bias due to such events to the peak integral above 80% of the nominal center-of-mass energy is $(-1.490\pm0.007)\cdot10^{-3}$ in the 500 GeV case and $(-1.424\pm0.007)\cdot10^{-3}$ in the 1 TeV case (before correction, the bias at both ILC energies is of order of 10%, and after correction it is 2 orders of magnitude lower). The errors are statistical.

The following is the list of sources of systematic uncertainty of the presented correction method:

- The assumption that $\vec{\beta}_{coll}$ is collinear with the beam axis,
- The use of the approximate angular differential cross section for the Bhabha scattering in the calculation of $w(\beta_{coll})$,
- Assumption in the calculation of β_{coll} and $w(\beta_{coll})$ that all ISR is lost and all FSR is detected.

The first of these three sources of uncertainty is responsible for the presence of the fraction of irreducibly lost events in the peak region above 80% of the nominal center-of mass energy. As said before, it induces a systematic bias of approximately 1.4 permille of the peak count which can only be corrected using the information from the beam-beam simulation. The variation of this bias due to the beam-parameter variations is smaller than 0.1 permille. After adding corrections for all the three sources of systematics, the average final uncertainty was calculated for both energy options, for the entire set of variations of the beam parameters (Chapter 3.1). The average final uncertainty of the Bhabha count is found to be $(+0.39\pm0.09)\cdot10^{-3}$ at 500 GeV and $(+0.67\pm0.10)\cdot10^{-3}$ at 1 TeV center-of-mass energy. However, the result is not simulation independent anymore.

One should note that the collision-frame method provides an accurate, simulation-independent reconstruction of the Bhabha counts in the upper 20% the of energy spectrum. It does not correct for the beamstrahlung induced counting losses below 80% of the nominal center-of-mass energy. For that purpose another method based on the features of the reconstructed luminosity spectrum is proposed and discussed in details in [4].

4.1.2 Electromagnetic deflection

Electromagnetic field of the opposite bunch is causing shift of the outgoing particles toward smaller polar angles. This shift is rather small, but since the Bhabha cross section is monotonously decreasing with the polar angle, the net effect of EMD is a decrease of the Bhabha count. This effect is equivalent to a parallel shift in the opposite directions of the angular limits θ_{min} and θ_{max} of the luminometer fiducial volume by an *effective mean deflection angle* $\Delta\theta$.

One can define variable x_{EMD} that stands for the proportionality coefficient between the effective mean deflection angle $\Delta\theta$ and the EMD-induced counting loss:

$$x_{EMD} = \frac{1}{N}\frac{dN}{d\theta} \tag{4.5}$$

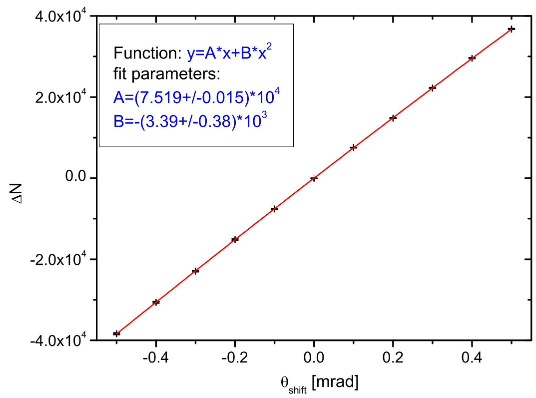

Figure 4. Fit of the $(dN/d\theta)_{sim}$ for the standard set of beam parameters at 1 TeV.

where N is the Bhabha count in the luminometer fiducial volume, and dN stands for the loss of counts induced by the shift $d\theta$ due to EMD. The counting loss translates into uncertainty of the measure luminosity as:

$$\frac{\Delta L}{L} = \frac{1}{N}\frac{dN}{d\theta}\Delta\theta \tag{4.6}$$

The value of $\Delta\theta$ can be obtained from simulation from the slope $dN/d\theta$, knowing the counting loss ΔN induced by EMD (Fig. 4). Figure 4 shows the fit of $(dN/d\theta)_{sim}$ for the standard set of beam parameters at 1 TeV. $\Delta N = N_{shift} - N_{FV}$ is the difference in counts in the shifted counting volume $(\theta_{min} + \theta_{shift}, \theta_{max} + \theta_{shift})$ and in the nominal fiducial volume $(\theta_{min}, \theta_{max})$. The statistical error of ΔN is estimated as $\delta(\Delta N) = \sqrt{n_{shift} + n_{FV}}$, where $N_{shift} = N' + n_{shift}$, $N_{FV} = N' + n_{FV}$ and N' is the number of events inside the intersection of the fiducial with the shifted counting volume. The slope $(dN/d\theta)_{sim}$ from Figure 4 is $(dN/d\theta)_{sim} = (7.519 \pm 0.015)\cdot 10^4\ mrad^{-1}$. Resulting effective mean deflection is $\Delta\theta = (0.0194 \pm 0.0006)\ mrad$, at 1 TeV center-of-mass energy, and it corresponds to the luminosity bias of $\Delta L/L = (-1.07 \pm 0.03)\cdot 10^{-3}$ induced by the electromagnetic deflection. In the same manner $\Delta\theta = (0.0426 \pm 0.0009)\ mrad$ is obtained at 500 GeV center-of-mass energy corresponding to the luminosity uncertainty of $\Delta L/L = (-2.39 \pm 0.05)\cdot 10^{-3}$.

If the simulated value of $\Delta\theta$ is returned to Eq. 4.6, it can be used in the experiment to determine EMD induced counting loss, knowing the experimentally determined value of x_{EMD}. Thus from the experimentally obtained quantity x_{EMD}, although not in a completely simulation independent manner, one can correct for the EMD induced counting loss. The precision of this correction depends on the precision with which the beam parameters are known. Figure 5 shows the scatter plot of the values of the EMD counting losses obtained using a fixed simulated value of $\Delta\theta$ versus the "real" EMD losses in the simulation for each set of beam parameters, with individual parameter variations up to 20% as described in Sec. 3.1. The error of the counting-loss estimate due to the beam imperfections is always smaller than $\pm 5\cdot 10^{-4}$ of the total luminosity in the 500 GeV case, and $\pm 2\cdot 10^{-4}$ in 1 TeV case. If the beam parameters are known with better precision (as discussed in [26]), the residual uncertainty of the EMD effect on integrated luminosity will be correspondingly smaller.

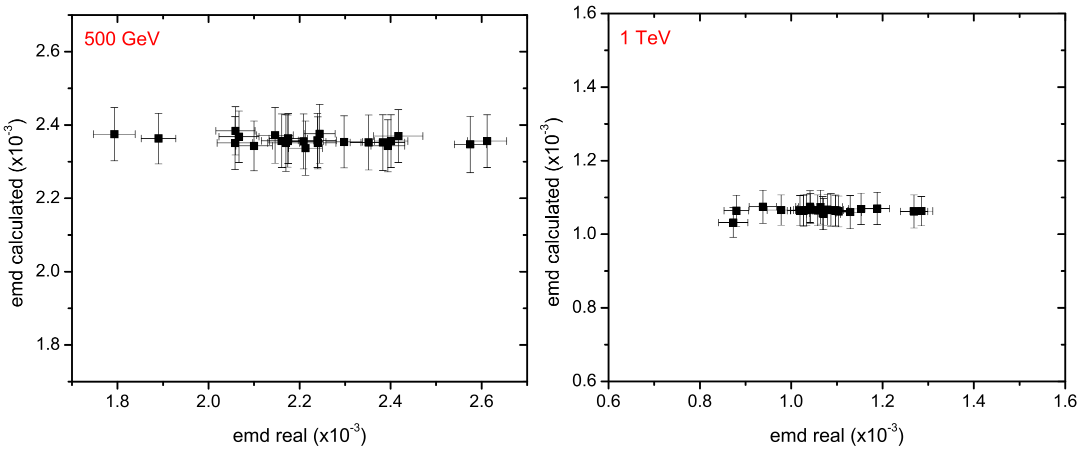

Figure 5. Scatter plot of the calculated EMD relative counting loss from $(dN/d\theta)_{sim}$ with a unique $\Delta\theta$ value derived for the nominal beam parameters, against the "real" EMD obtained directly from the difference in counts for a diverse range of beam imperfections, including the bunch geometry as well as the bunch charge variations. 500 GeV center-of-mass energy is assumed for the left plot and 1 TeV for the right one.

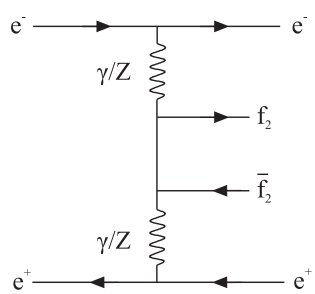

Figure 6. Two-photon exchange is the dominant Feynman diagram for the neutral current four-fermion production.

4.2 Background from physics processes

Another major systematic effect in the luminosity measurement originates from the four-fermion neutral current processes of the type $e^+e^- \rightarrow e^+e^- f\ \bar{f}$. These processes have Bhabha like signature characterized by the outgoing e^+e^- pairs emitted very close to the beam pipe carrying a large fraction of energy so they can be miscounted as a signal. The leading order Feynman diagram is given in Figure 6. The dominant contribution to the cross section comes from the multiperipheral (two-photon exchange) process.

Due to the steep polar angle distribution of the produced particles, only a few permille of the produced primary e^+e^- pairs are are deposited in the luminometer. The rest is detected in the beam calorimeter. Thus physics background is present in only 6.0 (2.2) permille at 500 GeV (1 TeV) of signal cases before any selection applied. Energy and polar angle distributions of signal and physics background in the acceptance region of the luminosity calorimeter, at 500 GeV center-of-mass energy are given in Figure 7. Similar distributions are obtained at 1 TeV center-of-mass energy as well. In Figure 7, depositions at the nominal beam energy come from the electron spectators. Physics background polar angle distribution (Figure 7) is similar to the one for the

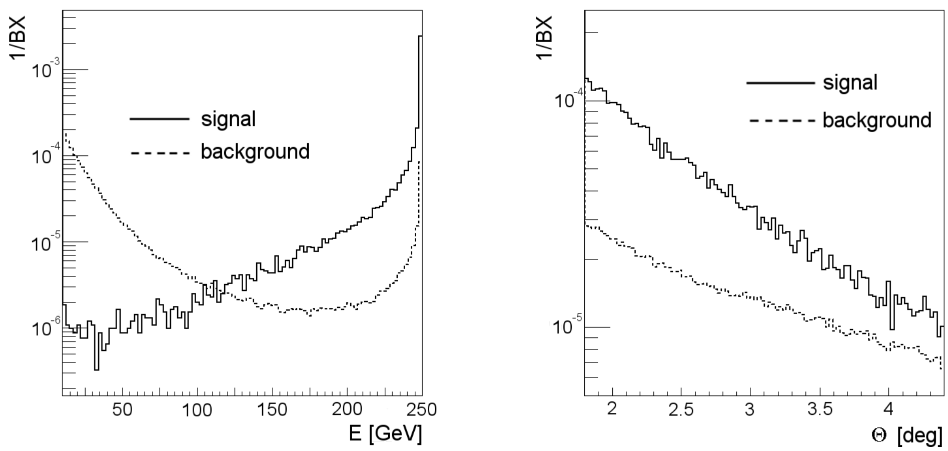

Figure 7. Energy (left) and polar angle distribution (right) of final state particles originating from signal and four-fermion processes, detected in the acceptance of the luminosity calorimeter, at 500 GeV center-of-mass energy.

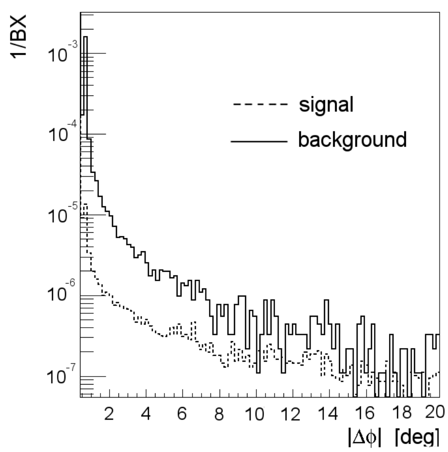

Figure 8. Difference in azimuthal angle of particles detected at the opposite sides of the luminometer are given for signal (dashed line) and background (solid line) at 500 GeV center-of-mass energy.

signal confirming the very forward nature of the four-fermion production.

Except for being collinear in the absence of the beam-induced effects, Bhabha events are also coplanar. Difference in azimuthal angle of particles detected at the opposite sides of the luminometer are given for signal and background in Figure 8.

Separation power of a selection is described by the two variables: signal efficiency E_s and background rejection R_{bck}:

$$E_s = \frac{N_s^{'}}{N_s} \qquad\qquad R_{bck} = 1 - \frac{N_{bck}^{'}}{N_{bck}} \tag{4.7}$$

where the N_s, N_{bck} correspond to the number of coincidently detected pairs at the opposite sides of luminometer, for signal and background respectively, while the prime values correspond to the number of selected events. Acoplanarity can be useful as a signal to background separation variable, giving the background rejection above 50% [6] for $|\Delta\phi| < 5^o$.

4.2.1 Event selection

In this paper we propose selection that optimizes influence of the leading systematic effects - beam induced effects and physics background. Event will be selected as a signal if a detected pair of particles carries more than 80% of the nominal center-of-mass energy and the difference between azimuthal angles of the reconstructed particles is less than 5^o. These selection criteria, being correlated to each other, are covering the same region of the phase space to a large extent. Selection based on any of the two criteria results in the background to signal ratios of the permille order [6]. However, the criterion on acoplanarity reduces in addition the fraction of events that would be irrecoverably lost from the detector fiducial volume due to the beamstrahlung and ISR, from approximately 1.4 permille to 0.4 permille at all ILC energies. Signal selection efficiency and background rejection for the proposed selections are given in the Table 1, for leptonic and hadronic background at 500 GeV and 1 TeV center-of-mass energies. Since NLO corrections for the four-fermion production cross section are not yet available at ILC energies, instead of correcting for miscounts due to the presence of background processes, we will assume the full size effect of physics background to the relative systematic uncertainty of the measured luminosity.

Table 1. Selection and rejection efficiencies (E_s and R_{bck}) for signal and background at 500 GeV and 1 TeV center-of-mass energies.

		500 GeV	1 TeV
Signal	E_s	94 %	94 %
Leptonic background	R_{bck}	60%	56%
$e^+e^- \to e^+e^-e^+e^-$	B/S	$1.6 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$
Hadronic background	R_{bck}	70 %	91 %
$e^+e^- \to e^+e^-q\bar{q}$	B/S	$0.6 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$
$\Delta L/L$		$2.2 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$

The cross section of the two-photon processes is rising with the center-of-mass energy as $ln^2(s)$ [27] and practically saturates at several nb in the vicinity of the ILC energies. On the other hand, the polar angle distribution of the high energetic electrons, which carry at least 80% of beam energy, is shifted toward lower polar angles thus the majority of the e^+e^- spectators from physics background are missing the luminometer. This change in topology will compensate the slight rise of the cross section resulting in improved B/S ratio at 1 TeV in comparison to the 500 GeV as visible in Table 1.

At all ILC energies, signal selection efficiency is maintained above 90%, while 56% to 91% of background is suppressed at different center-of-mass energies, depending on the type of four-fermion process. The above corresponds to the systematic uncertainty of the integrated luminosity

originating from physics background at the level of few permille or better, while the statistical error of the luminosity measured over a year of ILC operation is kept at the level of 10^{-4} due to the high signal efficiency.

4.3 Summary on systematic uncertainties in luminosity measurement

Various sources of systematic uncertainty that would have impact on luminosity measurement are discussed in details in [2] for the 500 GeV center-of-mass energy ILC. We take all the sources of systematic uncertainty as in [2], except for the beam-induced effects and physics background that are being revised. We extend the overview of systematic uncertainties to the 1 TeV center-of-mass ILC case. New results also include not only pinch effect and beamstrahlung, but also initial state radiation and electromagnetic deflection both at 500 GeV and 1 TeV (Table 2). Differently from [2], physics background is taken in its full size without assumptions on the cross-section uncertainty induced by NLO corrections at ILC energies.

Table 2. Summary on systematic uncertainties in luminosity measurement at ILC, with simulation independent[1] or dependent[2] corrections.

Source of uncertainty	$\Delta L/L$ (500 GeV)	$\Delta L/L$ (1 TeV)
Bhabha cross-section σ_B	$5.4\cdot 10^{-4}$	$5.4\cdot 10^{-4}$
Polar angle resolution σ_θ	$1.6\cdot 10^{-4}$	$1.6\cdot 10^{-4}$
Bias of polar angle $\Delta\theta$	$1.6\cdot 10^{-4}$	$1.6\cdot 10^{-4}$
Energy resolution a_{res}	$1.0\cdot 10^{-4}$	$1.0\cdot 10^{-4}$
Energy scale	$1.0\cdot 10^{-3}$	$1.0\cdot 10^{-3}$
Beam polarization	$1.9\cdot 10^{-4}$	$1.9\cdot 10^{-4}$
Physics background B/S	$2.2\cdot 10^{-3}$	$0.8\cdot 10^{-3}$
Beamstrahlung + ISR[1]	$-1.1\cdot 10^{-3}$	$-0.7\cdot 10^{-3}$
Beamstrahlung + ISR[2]	$0.4\cdot 10^{-3}$	$0.7\cdot 10^{-3}$
EMD[1]	$-2.4\cdot 10^{-3}$	$-1.1\cdot 10^{-3}$
EMD[2]	$0.5\cdot 10^{-3}$	$0.2\cdot 10^{-3}$
$(\Delta L/L)^1$	$4.3\cdot 10^{-3}$	$2.3\cdot 10^{-3}$
$(\Delta L/L)^2$	$2.6\cdot 10^{-3}$	$1.6\cdot 10^{-3}$

Uncertainties are assumed to be uncorrelated. The only exception is the remaining biases due to beamstrahlung and EMD in the case of simulation-independent correction. Since these biases are both negative by definition, they were linearly summed together and that sum is then added quadratically to the uncertainties from other sources. Uncertainty of the theoretical cross-section for Bhabha scattering is taken to be as at LEP energies [21]. As can be seen from Table 2, overall systematic uncertainty of luminosity is no larger than a few permille.

5. Summary

Interaction of the colliding beams introduce sizable bias of the order of 10 percent in luminosity

measurement at ILC energies. This dominantly comes from the energy loss of the initial state due to the beamstrahlung and ISR. Existing corrective techniques are simulation dependent and the systematic uncertainty of luminosity measurement depends on the knowledge of the beam parameters. Within the proposed selection, a method to correct for these effects in a simulation independent manner and practically without sensibility to the knowledge of the beam parameters is presented in this paper. It is demonstrated that the systematic bias induced by the beamstrahlung and ISR can be reduced by a factor of a hundred to the level of approximately 1.4 permille at ILC energies.

If the simulation is used to estimate the residual uncertainty of this effect instead of its full size, the uncertainty of the measured luminosity can be reduced to the less than a permille. In addition, simulation dependent corrections can be introduced to include already small effect (of order of a permille) of the electromagnetic deflection of the final state. The overall residual uncertainty of luminosity measurement induced by the beam-beam effects is in this case below permille.

Dominant source of uncertainty in luminosity measurement comes from the physics background taken as a full-size effect until reliable estimates of the cross-section for the four-fermion production at ILC energies become available.

Taking into account all the sources of systematic uncertainty of luminosity measurement we prove that the luminosity can be measured at ILC in the peak region above 80% of the nominal center-of-mass energy with the required precision of a few permille, even if one corrects for the dominant systematic effects without using the simulation-dependent information.

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